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Tracer Study of Vertical Exchange by Cumulus Clouds

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Tracer Study of Vertical Exchange by Cumulus Clouds

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ABSTRACT

This paper examines the exchange of material by convective cloud processes between the mixed layer and the overlying free troposphere. It describes results of a field experiment that was conducted in Lexington, Kentucky, during the period from 20 July to 24 August 1983 to study the processes associated with the vertical transport of acidic pollutants by nonprecipitating cumulus convection. An aircraft released SF_6 tracer either within or above the mixed layer, and it was sampled by another aircraft at various levels within or above the mixed layer in the active cumulus convective cloud zone, as well as on the ground. The results show that mixed layer pollutants are vented above the entrainment zone of its boundary layer into the overlying cloud layer by fields of active cumulus and that such active clouds may force cloud layer air downward into the mixed layer.

1. Introduction

Pollutants from the mixed layer are expected to be transported above the mixed layer by cumulus convective activity. The vertical extent of the transport should depend greatly on the vertical distribution and type of cumulus clouds, which in turn depends on the synoptic environment. Stull (1985) segregates cumulus convective clouds into forced, active or passive classes. Forced clouds are cumulus arising out of rising convective elements and are limited to but influential on the dynamics of the mixed layer entrainment zone; active clouds protrude into the overlying free troposphere beyond the mixed layer entrainment zone; and passive clouds are the decaying remnants of former active clouds whose bouyancy is spent and they are decoupled from the surface. Forced clouds will thicken the depth of the entrainment zone, and due to large spatial variability in cloud activity, they will cause a corresponding spatial variability in the height of the mixed layer. These fair weather clouds arise when thermal updrafts become saturated. The updrafts are observed to be strongest on the upwind side of the cells, and the compensating downdraft preferentially on the downwind side and considerably weaker, as discussed by Kunkel et al. (1977). Active clouds will be expected to "vent" mixed layer pollutants above the entrainment zone of the mixed layer. However, the areal extent of these active clouds is typically a small fraction of the the total cumulus cloud cover and is itself also highly variable in space. Passive clouds contain the mixed layer pollutants that continue to undergo heterogeneous in-cloud reactions and finally become cloud debris upon evaporation. These pollutants will undergo horizontal transport and influence deposition patterns different from those of the mixed layer. Multilayer regional acidic transport models need a practical scheme to compute the interlayer transport. Parametric schemes to calculate the net transport require detailed knowledge of the three-dimensional and temporal evolution of these convective elements. Systematic observation and subsequent analyses programs to document the flow field within and around a variety of nonprecipitating clouds of variable vertical extent are needed since, for parametric modeling requirements, present experimental data bases are inadequate.

The importance of these clouds in influencing regional scale air quality or acid deposition is currently being evaluated. Recent field investigations (Ching et al., 1984) support the hypothesis that some cumulus clouds can carry mixed layer pollutants into the free troposphere. This observational study utilized the NASA airborne UV DIAL system which remotely monitors the vertical profiles of ozone and aerosol backscatter below the aircraft. The air mass section that was observed during the afternoon contained active cumulus clouds which extended beyond 3500 m AGL and which penetrated the mixed layer (top about 1500 m AGL). It was monitored again in the early evening, long after the convective cloud activity ended and the clouds evaporated. The data showed a complex

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distribution and structure of polluted layers, which were inferred to arise from the dissipated clouds. These layers were tilted in the vertical as expected if a vertical cloud column is subjected to wind shear as was present on the sampling day; additionally, the ozone and the aerosol distribution were highly correlated within these layers. In other studies that utilized fast response ozone sensors and gust probe systems on aircraft, fluxes of ozone were measured for a field of convective cloud elements (Ching et al., 1983; Stull and Eloranta, 1984; Greenhut, 1986) and for clouds over an urban area (Greenhut et al., 1984). Aircraft studies by Alkezweeny et al. (1984) examined the vertical transport processes by nonprecipitating cumulus clouds and chemical transformations and conversion rates for sulfur compounds. The transformation rates from SO_2 to sulfate were found to be considerably faster and more complex than simple gas phase reactions. The data indicated average conversion rates of SO_2 to sulfate exceeding 10% per minute, (0.17% s^{-1}), but large variations were observed for different clouds and for different altitudes within clouds. Isaac et al. (1983) also argue that convective clouds vertically transport pollutants out of the subcloud layer. They define a vertical transport ratio, VTR, as the volume of subcloud air pumped through the cloud base relative to the total volume of the subcloud layer per hour. Their preliminary analyses suggest extreme VTR values of 50% in summer and 20% during the winter. Liu et al. (1984) analyzed 38 vertical profile measurements of Radon 222, an inert gas of continental ground origin. They concluded that 55% of the Radon 222 was transported out of the mixed layer during the summer months, while much smaller transport occurred during other seasons. Gidel (1983) modeled the vertical transport of transient tracers by cumulus clouds using a one-dimensional steady state entrainment model and cloud population imposed as an ensemble distribution of clouds of various heights. He found that pollutant mixing ratios will increase above a background that was not influenced earlier by cloud transport. Measurements by Chatsfield and Crutzen (1984) qualitatively substantiate Gidel's results. Liu et al. (1984) find that their Radon 222 profiles fall between Gidel's cloud and no cloud model results when applied to their data. Niewiadomski (1986) modeled the transport associated with a three-dimensional field of nonprecipitating cumulus clouds and also concluded that even relatively weak and sparsely distributed fields of such cumulus are very effective in removing pollutants from the mixed layer.

Large seasonal and spatial variability in cloud cover is to be expected, depending on synoptic conditions and climatic factors. However, for any given meteorological state, the net exchange rate cannot be predicted or modeled with great certainty since direct flux measurements over grids of regional scales have not, as yet, been successfully measured and current understanding of these processes is limited. Furthermore, there is currently no verification of model schemes that predict the exchange and conversion rates by these nonprecipitating clouds.

The observational evidence that vertical transport indeed occurs is limited and inferred. There is little, if any, direct observation to substantiate actual transport by cumulus clouds. During July and August 1983, Battelle, Pacific Northwest Laboratory (PNL) conducted an experimental research program in the vicinity of Lexington, Kentucky, to study and understand the transport and transformation processes associated with nonprecipitating cumulus clouds for use in supporting the development of regional-scale acid precipitation models. This program was part of the National Acid Precipitation Assessment Program (NAPAP). This paper provides results of three transport experiments that utilized tracer gas inserted below and above cumulus clouds. Two of the studies show that the active cumulus clouds transport mixed layer air upward into the overlying free troposphere above the entrainment zone. The remaining study suggests that fields of active cumuli induce rapid downward transport of air from the free troposphere into the mixed layer.

2. Description of experiment and results

A nonreactive tracer, sulfur hexafluoride (SF_6) gas was chosen to track air parcel trajectories in and out of the clouds. This tracer was chosen because it is nontoxic, easy to measure in parts per trillion concentrations, and relatively inexpensive to use. The SF_6 background is about 1 pptv, so relatively small amounts would be required for short-range/time-scale studies, e.g., less than 50 km per 4 h. The SF_6 was transferred from a large, pressurized cylinder into two propane tanks so that a total of 4.5 kg was contained in each tank. The tanks were connected to a flow control regulator and a flowmeter. The gas was released at the rate of 0.5 $m^3 s^{-1}$ for approximately 1 h for each of the experiments. Extreme caution was taken to avoid contamination of the sampling and detecting equipment. One aircraft was used for the SF_6 release, while a second one performed the sampling. During the SF_6 release, the sampling aircraft was stationed several kilometers downwind of and at a different elevation from the release aircraft. The samples were collected in tedlar bags for later analyses. Each bag was flushed twice with clean air, checked for contamination, and inflated with clean air. The bags were deflated only a few seconds before sampling. It took approximately 30 s to fill each bag with outside air. Therefore, a sample concentration is an average over a distance of about 2 km for the aircraft speed of 64 m s^{-1}. The gas monitor was at a different location, far from the SF_6 storage and release system. This precaution was found to be necessary to ensure that the bags were free from contamination. The monitor was a commercial gas chromatograph instrument based on an electron capture detection principle. Before

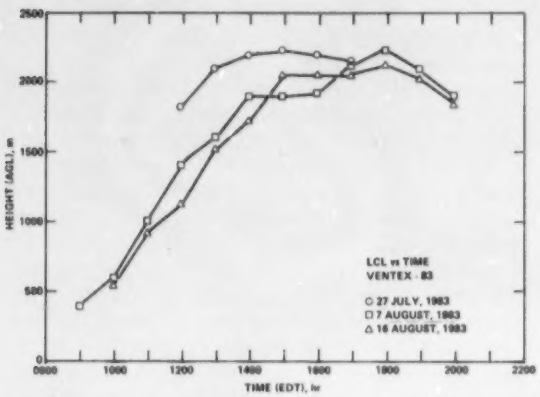

FIG. 1. Time series of computed lifting condensation levels (LCL) for 27 July 1983: line with circles; 7 August 1983: line with squares; and 16 August 1983: line with triangles. Data from the Blue Grass Airport, Lexington, Ky.

each test this monitor was calibrated with standard SF_6 concentrations.

During each operation day, pilot balloons were launched from the ground to determine the wind speed and direction at different altitudes. Based on this information, the tracer release location and sampling aircraft route were determined. The sampling aircraft obtained vertical profiles of temperature, relative humidity and aerosol backscatter prior to starting the tracer sampling pattern. From this data, mixed layer heights were derived. Additionally, the tracer release aircraft also performed vertical soundings to determine mixed layer heights using an on-board nephelometer and provided visual observations of the cloud fields during the experiments. Hourly surface observations from the NOAA weather station at Lexington's Blue Grass Airport were available; this station was within 80 km of all the tracer releases. Hourly lifting condensation levels (LCL) were derived from these data and are shown in Fig. 1. These values were consistent with values derived using the Barnes computational scheme for LCL (Barnes, 1968). Figure 2 provides a summary of the relevant operational and meteorological parameters for the three case studies. The symbols used in this figure are defined in the caption.

a. Upward transport studies

Tracer gas was released below nonprecipitating cumulus convective clouds and tracked in the mixed and cloud layer on two separate occasions, 27 July and 7 August 1983. Surface high pressure regimes dominated the synoptic-scale flow prior to and during both case studies. On 27 July, the surface high was centered over the New Jersey coast, having propagated southeastward

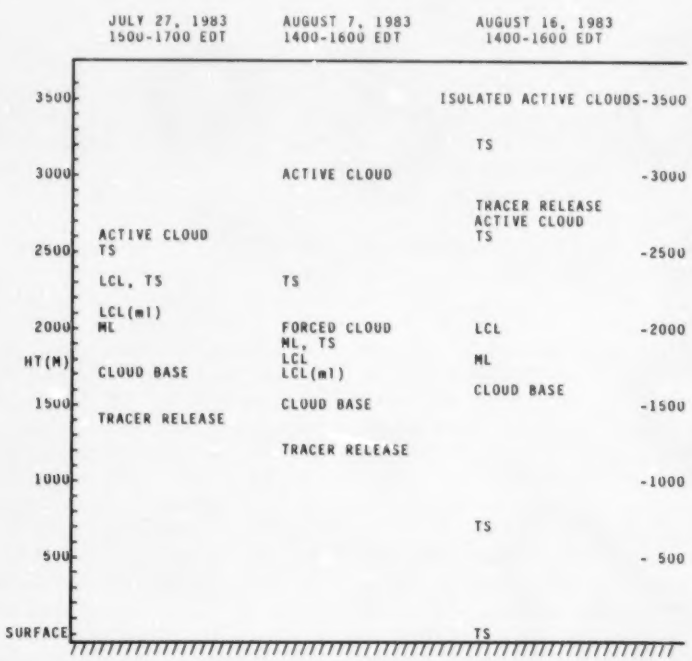

FIG. 2. Environment and experiment parameters for (a) 27 July, (b) 7 August and (c) 16 August 1983. Tracer sampling altitude is TS; ML the top of the observed mixed layer; and LCL (ml) the lifting condensation level from a sounding, excluding the first 100 m.

from the Great Lakes area from the previous day. The flow at 500 mb was dominated by an eastward-moving ridge line located just west of Lexington at the time of the sampling study. At that altitude, winds were generally northerly, and speeds were less than 10 m s^{-1} and decreased with time. The surface winds on the twenty-seventh were southeasterly during the morning, shifting to southwesterly in the afternoon at the time of the tracer study. The surface wind speeds varied from 2 to 3.5 m s^{-1}. The experimental day was characterized as hazy, with visibility limited to 10 km. Maximum surface temperature was 32°C and the dewpoint was 12°C at 1700 EDT. Except for a trace that occurred 4 days earlier, there was no other precipitation reported for the previous 13 days. Cumulus cloud cover changed from 10% at 1300 EDT to over 50% by the start of the tracer release at 1512 EDT. The base of the temperature inversion determined from aircraft soundings was observed to increase in time from approximately 1600 m AGL at 1145 EDT to 1800 m AGL at 1220 EDT and leveled off to just under 2000 m AGL from 1415 EDT throughout the rest of the tracer study. Fair weather type cumulus clouds started to form at approximately 1100 EDT. Cumulus cloud bases were observed from the aircraft to be below the temperature inversion throughout the study period, starting from under 1000 m AGL before local noon and rising to about 1700 m AGL at the time of the tracer release. Cumulus cloud tops were noted to be at about the base of the temperature inversion before noon, but at 1500 EDT active cumulus convective cloud elements, protruding about 200 m beyond the indicated mixed layer, were observed; tops were generally around 2200 m AGL with some turrets extending to nearly 2500 m AGL. The computed LCL shown in Fig. 1 was greater than the indicated mixed layer height throughout the day. A mixed layer lifting condensation level, LCL (ml), was also computed to represent conditions at the top of the surface layer (by assuming a convective parcel originates at about 100 m above and at a potential temperature 1°C colder than at the surface) in order to indicate a range of probable source heights for the cumulus. It can be seen in Fig. 2 that LCL (ml) is also above the indicated mixed layer. According to Wilde et al. (1985), convective cumulus can exist when the LCL is higher than the mixed layer under the condition that the zone of entrainment between the mixed layer and the free troposphere and the zone of LCL overlap. Data on the width of both zones are not available for this study, but the difference between the LCL and the mixed layer was about the same or smaller than those in the study by Wilde et al. (1985).

The SF_6 tracer was released for a period of 1 h starting at 1512 EDT at a location about 70 km northeast of Lexington at an elevation of 1400 m which was about 300 m below cloud bases; release was along a line 16 km long oriented across the prevailing wind direction at this altitude. The sampling aircraft collected bag samples between 1524 and 1543 EDT at a constant altitude of 2200 m (the height of the predominant cloud tops of the active cloud as determined by the on-board observer) but below the tops of the highest clouds. Sampling was also conducted between 1550 and 1630 EDT at 2500 m (the elevation of the tops of the highest clouds) where additional bag samples were collected. Figure 2 depicts the critical operational and environmental parameters for the study. Figure 3 shows the release line and the sampling aircraft flight route. The tracer concentrations are shown superimposed on the flight route.

A second test similar to that of the first was conducted on 7 August 1983. A weak surface high pressure area extended across the United States. Surface winds were generally from the east and northeast sector throughout the experimental day with speeds ranging from 2 to 4 m s^{-1}. The 500 mb flow field was characterized by a ridge over the Rockies throughout this study period, resulting in northerly, but weak (decreasing from about 10 m s^{-1} to less than 5 m s^{-1}) winds, which became more northeasterly the following day. The day started out hazy, but visibility increased from 7 km in the morning to 12 km by the afternoon. The tracer was released for one hour starting at 1430 EDT. Cloud cover increased from about 50% prior to local noon to 70% during the time of the tracer study. Mixed layer height rose from 1800 m AGL at 1330 EDT to 2000 m AGL in the midafternoon after the tracer release. Temperature (and ozone) soundings in this experiment are indicated in Fig. 4 for 1600 EDT. The computed LCL as shown in Fig. 1 indicates a steady rise from 400 m AGL at 0900 EDT to 1900 m AGL at the start of the tracer release. Thus, the indicated mixed layer was only slightly higher than the calculated LCL. From the discussion found in Wilde et al. (1985), one

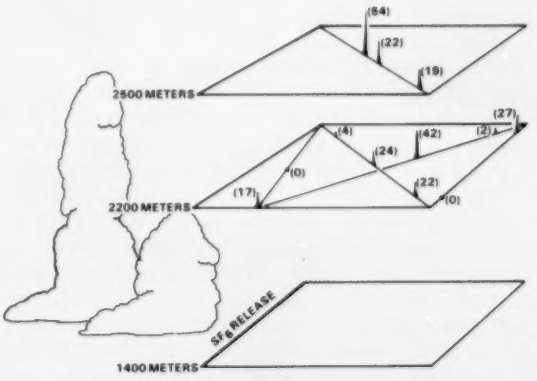

FIG. 3. Sulfur Hexafluoride (SF_6) release and sampling routes on 27 July 1983. Numbers in parentheses are concentrations in parts per trillion of SF_6 gas.

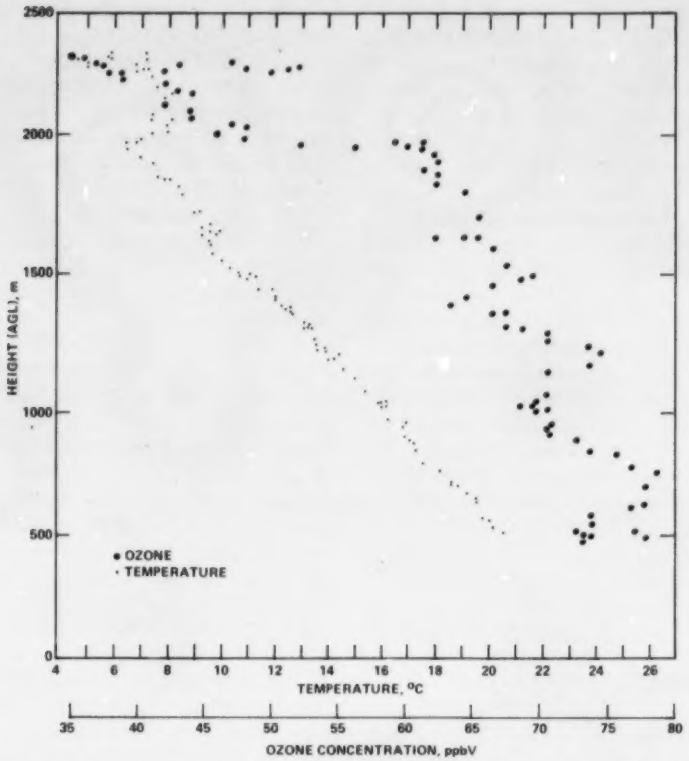

FIG. 4. Temperature and ozone profiles for 7 August 1983 from aircraft soundings.

should expect cumulus development for this experiment.

Cumulus clouds began to form at about 1100 EDT, and by 1300 EDT, the cloud fields contained both forced and active type clouds (Stull, 1985) with aircraft observations showing cloud turrets extending higher than 2 km AGL and some Cb's in the distance. Surface observations also indicated towering Cu developing over all quadrants. Cloud bases were observed from 1400 m AGL at 1230 EDT and only increased to just below 1500 m AGL by 1500 EDT. At the start of the tracer release, cloud tops of the forced variety were generally about 2000 m AGL, with towering or "active" cumulus development extending to greater than 3000 m AGL.

The SF_6 tracer was released at an altitude about 1250 m AGL along a 16 km line perpendicular to the wind. The second aircraft began sampling about 45 min after the start of the release for a duration of 30 min. Two flight altitudes were selected for sampling, one just at the top of the entrainment, forced cloud top zone at 2000 m AGL, and the other within the active cloud layer at 2300 m AGL. The critical experimental parameters are shown in Fig. 2. The analysis results of the bag samples are shown in Fig. 5.

b. Downward transport

The layer above the mixed layer that receives mixed layer mass by way of protrusions by venting or active type cumulus clouds must return an equivalent amount back into the mixed layer in order to maintain a state of mass equilibrium. The return might be rapid and vigorous and therefore of small areal extent, or it may

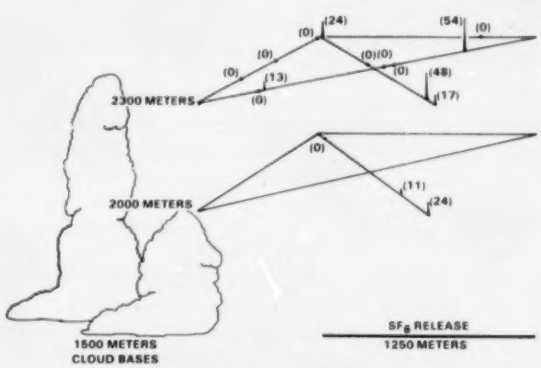

FIG. 5. As in Fig. 3 but for 7 August 1983.

proceed to subside slowly over a large area. In either case, this mass transport would occur relative to the existing synoptic-scale vertical motions. Thus, the nature of the exchange is not yet well understood.

During VENTEX-83, a tracer experiment was designed to examine the nature of the vertical transport from the cloud layer into the mixed layer. By design, a tracer would be released at an altitude above the mixed layer, but within the layer where active clouds are present, and subsequently tracked at different levels in the vertical. The rate of transport would then be determined by reference to the time and height where the tracer could be detected. Such an experiment was conducted on 16 August 1983 and is described below.

On this day, a stationary area of high pressure at the surface dominated the mixed layer flow with its center over New Jersey. Over Lexington, weak southeasterly flow on 15 August changed slowly to southwesterly on 17 August 1983. Surface wind speeds varied from 2 to 4 m s^{-1}. The 500 mb flow was also dominated by a region of high pressure centered over Kansas during this study. Winds at that level were northerly and light (about 8 m s^{-1}) locally. There was no reported precipitation on this or the previous four days. The indicated height of the mixed layer from aircraft soundings was greater than 1800 m AGL at 1500 EDT. The maximum surface temperature of 32°C was observed at 1400 EDT; the corresponding dewpoint was 14°C. The LCL shown in Fig. 1 increased steadily from about 500 m AGL at 1000 EDT before leveling off above 2000 m AGL by 1500 EDT, or just above the mixed layer. The computed LCL (ml) for assumed conditions at the top of the surface layer, i.e., 100 m, is at nearly the same altitude as the indicated mixed layer. These observations would probably satisfy the requirements by Wilde et al. (1985) for the development of cumulus clouds. The day started with broken clouds that decreased to scattered altocumulus clouds prior to the onset of cumulus clouds at about 1130 EDT. By 1300 EDT, the cumulus cloud cover was 20%, and it increased to 70% by the afternoon, under very hazy conditions with visibility limited to 8 km. Cloud bases were observed between 1100 and 1400 m AGL. The cumulus clouds were observed to undergo vigorous vertical development for all quadrants. The tops of the cumuli were observed to rise from 2100 m AGL at 1300 EDT to 2500 m AGL at 1400 EDT at the start of the tracer release, and to 2700 m AGL at 1500 EDT, the end of the release. These heights were significantly higher than the computed LCL's or the top of the mixed layer, and it is clear that a large fraction of the clouds present must have been of the "active" or venting type. Numerous cloud turrets were observed (estimated) to extend above 3500 m AGL at this time. Figure 6 is a photo taken of the clouds in the vicinity of and during the tracer experiments. Note the cumulus congestus in the near forground and the Cb in the distance.

The SF_6 tracer was released in a back-and-forth pattern from 1400 to 1500 EDT along a given 16 km line with a crosswind orientation at heights corresponding to the heights of the predominant cloud tops. The altitude of the release was necessarily increased from 2500 m AGL at the start to 2670 m AGL at the end of the release to conform to the rise of the cloud tops during this period. Sampling was done both aloft and on the ground downwind of the release site, at the Lex-

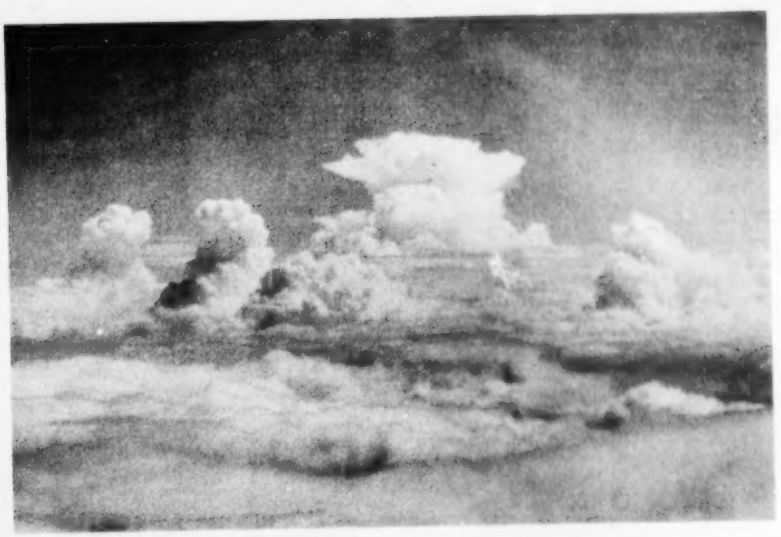

FIG. 6. Photograph of the cloud field at the time of tracer release on 16 August 1983, showing the top of the active cumulus cloud deck at 2500 m AGL and cloud turrets at higher elevations.

ington Airport site. The flight path and the results of the aircraft sampling are shown in Fig. 7. Note that the first airborne sample was taken at about 3200 m AGL, more than 500 m above the tracer release altitude, and about 900 s after the release was stopped (from 1514 to 1530 EDT). The aircraft then descended to 2400 m, within the cloud layer, and sampled from 1554 to 1638 EDT. The final sample collection was made within the boundary layer at 680 m above the ground, 620 m below cloud bases. The critical experimental parameters are indicated in Fig. 1. Syringe samples were taken at the ground at approximately 300 s intervals. The results of the ground measurements are shown in Fig. 8.

3. Discussion

The experiments of 27 July and 7 August 1983 provide some insights into the process by which clouds transport air out of the mixed layer. In these two studies, SF_6 was released below cloud bases and subsequently observed at the top of the entrainment zone and also above this level (but within the layer where active clouds exist). The SF_6 measurements exhibited large variations between samples, and the concentrations were much larger than can be supported under typical turbulent diffusion mixing conditions. This can be demonstrated by an order of magnitude analysis. For an SF_6 emission rate of about 0.5 $m^3 s^{-1}$ at constant elevation along a crosswind path of 16 km, flown repeatedly over a 1-h period and with a 3 m s^{-1} advecting wind, these emissions would cover an area of approximately 200 km^2. If the tracer is assumed to be uniformly and instantaneously mixed through a depth between the surface and the tops of the active clouds, say about 2.5 to 3 km, which corresponds to a volume on the order of 500–1000 km^3 or larger, the resulting SF_6 mean values will be on the order of 5 ppt or so above its present background value of about 1 ppt. However, the observed concentrations above the entrainment zone but within the layer of venting clouds were significantly larger: concentration values representing 2 km sampling distances varied from background value to greater than 50 ppt. These measurements suggest that some of the tracers are entrained soon after release—and are therefore relatively undiluted—into the thermals that become cloud updrafts, some becoming clouds of the active or penetrating type. Ultimately, these clouds become passive and, finally, upon evaporating, deposit the tracers into the stably stratified free troposphere. The large variation observed in the tracer samples attests to processes that are highly episodic in nature. It is quite possible that some of the tracers in the samples collected just above the mixed layer may be associated with its entrainment processes. However, it is highly unlikely that the tracers in the samples taken at the higher altitude flight could have been explained by the processes of entrainment. It is more probable that these samples arrived at that altitude by the active venters.

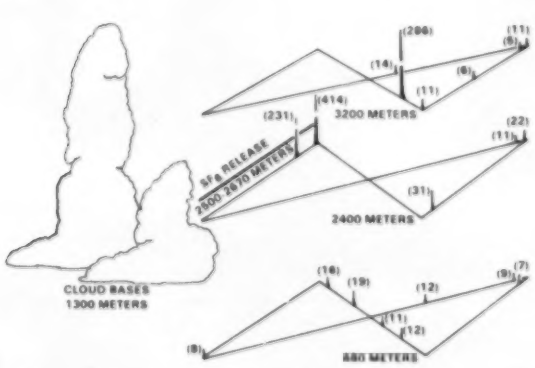

FIG. 7. As in Fig. 3 but for 16 August 1983. The release coordinate points are 38°06'N, 84°55'W and 38°15'N, 85°50'W.

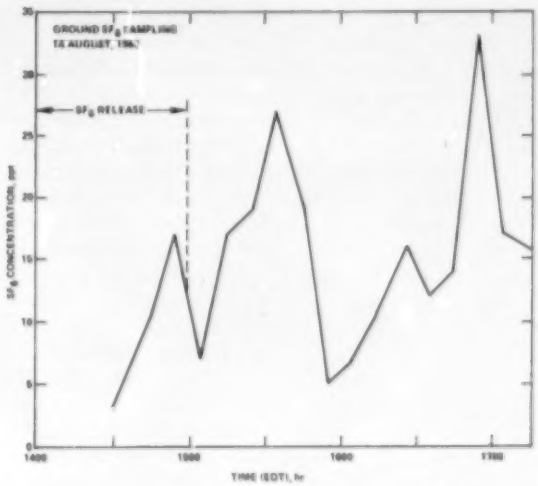

FIG. 8. Concentrations of SF_6 measured on the ground and downwind of the release line for 16 August 1983.

The case study of 16 August provides insights into the exchange processes from the free troposphere down into the mixed layer induced by these nonprecipitating clouds. In this experiment, the tracer was released in a manner identical to the other previously described cases but at the altitude of the top of the general cloud field, which we believe were active type clouds (Fig. 7). It is unlikely, for example, that the entrainment zone could have extended more than 700 m above the mixed layer. The bag samples taken by aircraft within 0.5 h after the end of the tracer release and 500 m above its release altitude (which was still well within the zone of the active clouds) showed very large concentrations and great sample-to-sample differences. This result is con-

sistent with the findings of the other two tracer experiments and provides additional evidence that these venting type clouds do move mass to greater altitudes. The samples taken within 1.5 h after and just at or within 200 m below the altitude of the release also show large and variable values of concentrations. The largest concentrations of several hundred ppt are about the same magnitude as that observed at the higher level. The magnitude is consistent with the average centerline crosswind concentration computed using a Gaussian plume dispersion model.

The important aspect of this scenario was the clear evidence that the tracer experienced rapid downward movement within the layer of active clouds, entered the mixed layer, and arrived at the surface. These observations suggest that the downdraft velocities for a significant fraction of the compensating area are large and in close proximity to the updraft region of individual cloud elements. The reasoning behind this hypothesis is as follows. If the mass balance proceeded as an augmentation to the general synoptic scale subsidence, and if such resulting subsidence were very large, say on the order of 0.05 m s^{-1}, the tracer released 800 m above the mixed layer would arrive at the top of the mixed layer about 5 h or so later. In this example, that time would be after 1900 EDT, well after the experiment was completed. Further, at that time, the ability to entrain this material into the mixed layer would be limited, since the turbulent intensity at this time of the diurnal cycle is markedly reduced, and probably would not arrive at the surface until subjected to convective mixing the next day. Clearly, the tracer was observed a short time after release in cloud layers at levels both higher and lower than its release level. The sampling conducted at about 650 m AGL, or 0.4 of the mixed layer height, started about 2 h after the end of tracer release and about 1800 m below the release altitude. Concentrations greater than 10 ppt were observed after 1700 EDT, and greatly in excess of the 1 to 5 ppt values that would have been observed if the tracer were uniformly distributed within the mixed layer.

The surface measurements shown in Fig. 8 show that the tracer reached the surface within 0.5 h from the time of the start of the release. This would have to be accomplished by a circulation where the magnitude of the downdrafts averaged more than 1.5 m s^{-1}, which is considerable larger than synoptic-scale subsidence and is of the order of the vertical velocities of the large mixed layer convective eddies. The surface measurements showed the SF_6 concentration to be highly intermittent with values varying between 5 and 30 ppt. Unfortunately, the data collection period was terminated before all the tracer was advected out of the sampling region. Note that the aircraft sampling in the mixed layer occurred near the end of the period of sampling at the surface. Surface concentrations were comparable in magnitude to those measured by aircraft in the mixed layer. The rather long duration with which tracer was observed at the surface was unexpected. Details of the wind field time–height cross sections from pibal data available up to the time of the tracer release are shown in Fig. 9. At that time, the low-level flow from the southerly direction backed with height to a westerly flow at the top of the mixed layer to north-northwest at the tracer release altitude. Wind speeds were light throughout this depth of 2–3 m s^{-1}, except at the surface, where the winds were more variable.

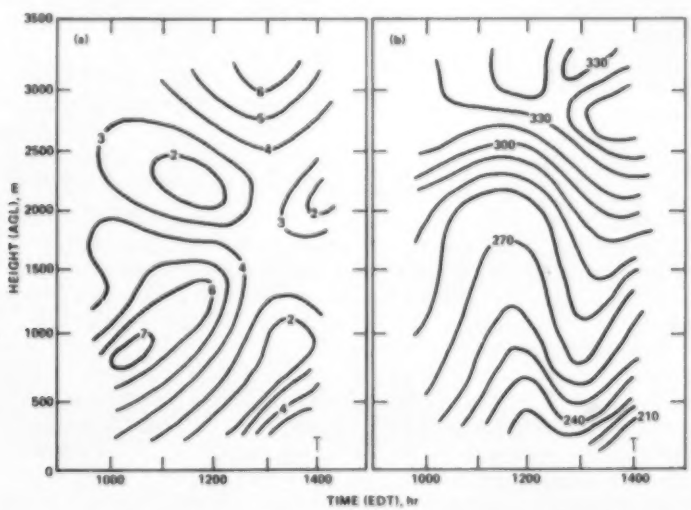

FIG. 9. Time–height wind field cross section for (a) wind speed (m s^{-1}) and (b) wind direction from pibal data for Lexington, Ky. on 16 August 1983.

Tracers released aloft as an area source can be visualized to enter a circulation pattern starting with a south-southeast drift, be pulled downward to the surface by the downward motion induced by the active cumulus clouds, and then drift in a northerly direction near the surface. This type of circulation will maintain the presence of tracers at the surface long after they ordinarily would have been expected to drift out of the sampling vicinity. Further, we envision that those tracers caught in early downdrafts and those caught in later downdrafts may still make their way to a common surface area, but will be separated in time. Unfortunately, real-time monitoring of the SF_6 was not available to indicate the appropriate time to terminate the sampling, which, in retrospect, was too soon.

This study strongly suggests that the downdrafts are induced by a field of dense and active venting clouds vigorous enough to transport mass from levels that are in the layer of the active clouds directly into the mixed layer. There is also some evidence that this forced circulation may extend all the way to the surface. However, it is possible that downward transport of cloud layer mass, once within the mixed layer, may occur as a result of being entrained into the circulation pattern of the large eddies of the mixed layer. In turn, the circulation of these large eddies may be strongly influenced by cumulus clouds of the forced type (Stull, 1985).

Finally, there appears to be some indication of a positive trend in the surface measurement of the SF_6 tracer. This is probably attributable to sampling variability. As a matter of considerable speculation we might imagine an alternate explanation. Given that (i) tracer released in the free troposphere fumigates into the mixed layer as a result of these downdrafts, (ii) its deposition to the surface is small, and (iii) horizontal advection is limited or negligible, the SF_6 concentration in the mixed layer should increase as a consequence of a negative vertical flux divergence. However, this situation cannot be proven from this set of limited observation.

Other recent observational studies favor the return pathway to be near or adjacent to the updraft region and of comparable magnitude to the updraft speeds. Kitchen and Caughy (1981), using a tethered balloon, observed a "P" shaped distribution. They suggest that a mechanism called CIFKU (Convective Instability of the First Kind Upside down), proposed by Randall (1980), is consistent with their observations. Uthe et al. (1985) released a cloud of nontoxic fluorescent dye particles both below and above cumulus clouds and monitored the transport and dispersion of these tracers using an airborne lidar. They observed that the dye released below clouds was vented upward into the clouds; the dye released at and above the tops of the cloud rapidly descended into the mixed layer. In both studies, however, the cloud fields were probably primarily forced clouds. Smolarkiewicz and Clark (1985), using the Large Eddy Simulation (LES) technique for modeling a field of convective clouds, find local subsidence regions adjacent to these clouds that penetrate a considerable depth into the PBL. Knupp and Cotton's (1985) interpretive review of convective-cloud-induced downdrafts suggests downshear downdrafts at cloud edges to be pronounced (of the order of several meters per second) and comparable in magnitude to the updrafts. Further, these downdraft scales were typically smaller than 1 km for the fair weather cumulus clouds.

Thus these tracer experiments provide evidence to support the rapid downdraft transport concept. However, this inference is based on only one case study and several other limited experimental studies. Due to the importance of this aspect of the process, it is strongly recommended that this hypothesis be vigorously and thoroughly tested. The implication of this result is that in the presence of cumulus convective cloud activity the layer of turbulent mixing is deeper, more vigorous, and apt to be localized within the domain of the cloudiness. As a consequence, an area supporting such a cloud field should experience a more rapid dilution of mixed layer pollutants and a fumigation of the free tropospheric pollutants into the mixed layer.

4. Conclusions

The results of these tracer experiments suggest that mixed layer pollutants can be lifted above the entrainment zone of the boundary layer into the overlying free troposphere or cloud layer by nonprecipitating, but active or venting-type cumulus clouds, as described by Stull (1985). This type of cloud penetrates deep into the free atmosphere, and when the clouds' excess bouyancy is spent they become passive, eventually evaporate, and thus leave the transported material aloft. Additionally, this study provides evidence that suggests that these types of cloud induce circulations transport air vigorously from the cloud layer into the entrainment zone. The limited evidence suggests, but does not necessarily lead to the conclusion, that this circulation may proceed all the way to the surface.

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